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Analytical Evaluation of Properties of Blast-Furnace Slag Providing Proper Operation of Furnace in Transient Conditions

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Calculation-analytical investigation of composition and high temperature properties of charge materials and properties of primary and final slag from blowing-in burden during furnace shutdown is accomplished for JSC "ArselorMittal Kryvyy Rih" and JSC "Severstal" with the use of monitoring and control system of slag mode of blast-furnace smelting. The limiting values of physical and chemical properties of primary and final slag in the working mode, during blowing-in and blowing-out operations are determined.

Keywords: BLAST FURNACE, BLOWING-IN, BLOWING-OUT, CHARGE MATERIALS, SOFTENING AND SMELTING TEMPERATURE, BLAST-FURNACE SLAG, PROPERTIES OF SLAG, VISCOSITY, ENTHALPY

Introduction

Under unsteady conditions of furnace operation the properties of primary and final slag melts formed from charge materials should provide fault-free and stable operation of blast furnaces. When blast-furnace blowing in, the processes of formation of softening and smelting regions of charge materials are important for maintenance of stable running of the furnace. During furnace shutdown, slag regime determines drainage ability of furnace providing a uniform distribution of smelting products and promotes removal of protective slag lining.

A limited number of publications are devoted to estimation of technological role of slag melts in maintenance of fault-free and stable operation of the furnace at blowing-in and blowing-out.

The purpose of present research is calculation-analytical estimation and determination of limiting values of physic-chemical properties of blast-furnace slag during blow-in and blow-out as compared to working regime of blast furnace operation at Ukrainian plants.

Results and Discussion

It is important to know melting points of charge materials and properties of primary and final slag in order to provide the most rational conditions, namely preheating of charge materials, targeting effect on slag formation processes related to formation of softening zone, primary, intermediate and final slag during blowing-in and blowing-out.

To forecast properties of iron-ore materials the generalized model of aggregate transformations developed in Z. I. Nekrasov Iron & Steel Institute of National Academy of Sciences of Ukraine is applied. The technique is presented in works [1-3]. Such model allows pretest analysis of meltability of iron-ore materials and selection of purposeful regime of their charging according to technological instruction during blowing-in and blowing-out periods.

Processing of initial data on the basis of "convolution" of chemical composition and melting points of various not recovered sinters, pellets and iron ore makes it possible to make models for forecasting these properties in the form of equations:

$$T^o = f(Fe_2O_3, FeO, \Delta e, \rho) \qquad \text{(Eq. 1)}$$

where Δe - chemical equivalent of charge composition; ρ - stoichometry parameter of structure [1]. Taking into account recovery extent

(*R)* we obtained equations for calculation of initial and finish melting temperatures for sinters and converter slag, pellets and ore [3]:

$$T^{R} = f(T^{o},\cdot R) \qquad \text{(Eq. 2)}$$

Developed models for forecasting composition and high-temperature properties of charge materials and corresponding properties of primary and final slag are implemented in the monitoring system of blast furnace slag regime "Shlak" approved at the number of blast furnaces and developed by Z. I. Nekrasov Iron & Steel Institute of National Academy of Sciences of Ukraine [4-6]. Properties of blast-furnace slag are computed with the use of system "Shlak" for blowing-in burdens on BF-8, 9 JSC “ArselorMittal Kryvyy Rih” and BF-5 JSC "Severstal" (**Figures 1, 2**). Intervals of change of stoichometry physic-chemical criteria ρ and physic-chemical equivalent of slag composition Δe specified in **Figure 2** correspond to boundary conditions and technology requirements to final slag providing proper running of blast-furnace and iron smelting in BF-9. The time history of primary slag properties (**Figure 1**) shows the regularities of early slag viscosity change.

Blowing-in burden is distributed by big blocks from the top to bottom of blast furnace, and the bottom furnace is presented by coke only. Therefore early slag from bottom furnace (tuyere belt - furnace waist) represents the slag formed by coke ash. In this case, dominant substances are SiO_2 - approximately 50 % and Al_2O_3 - 20-30 %, other components are presented in insignificant quantity. So this slag appears to be very viscous when blowing the furnace. However, considering that during the first hours of operation early slag is formed in the peripheral zone, this slag is flowing near furnace walls. Considering its viscous condition, it is necessary to expect its deposition on heated not enough walls of bosh, hearth and metal receiver.

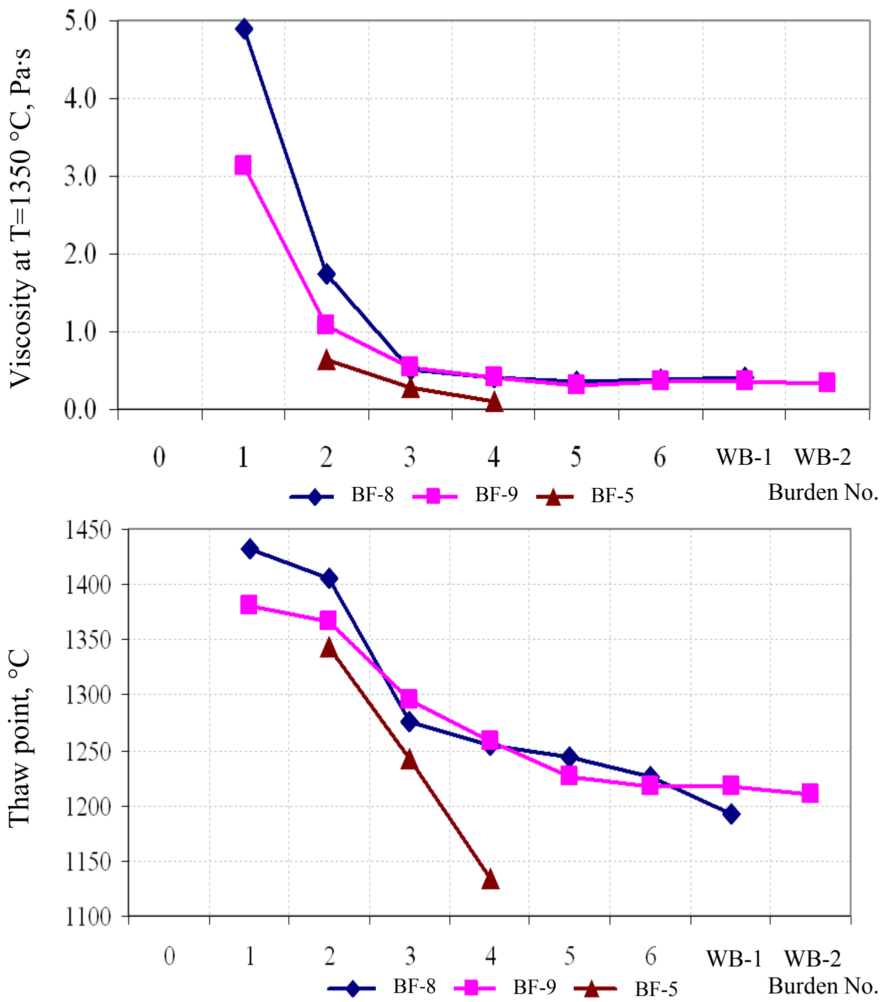

Figure 1. Time history of primary slag properties of blowing-in burden in BF-8, 9 JSC “ArselorMittal Kryvyy Rih” and BF-5 JSC "Severstal"

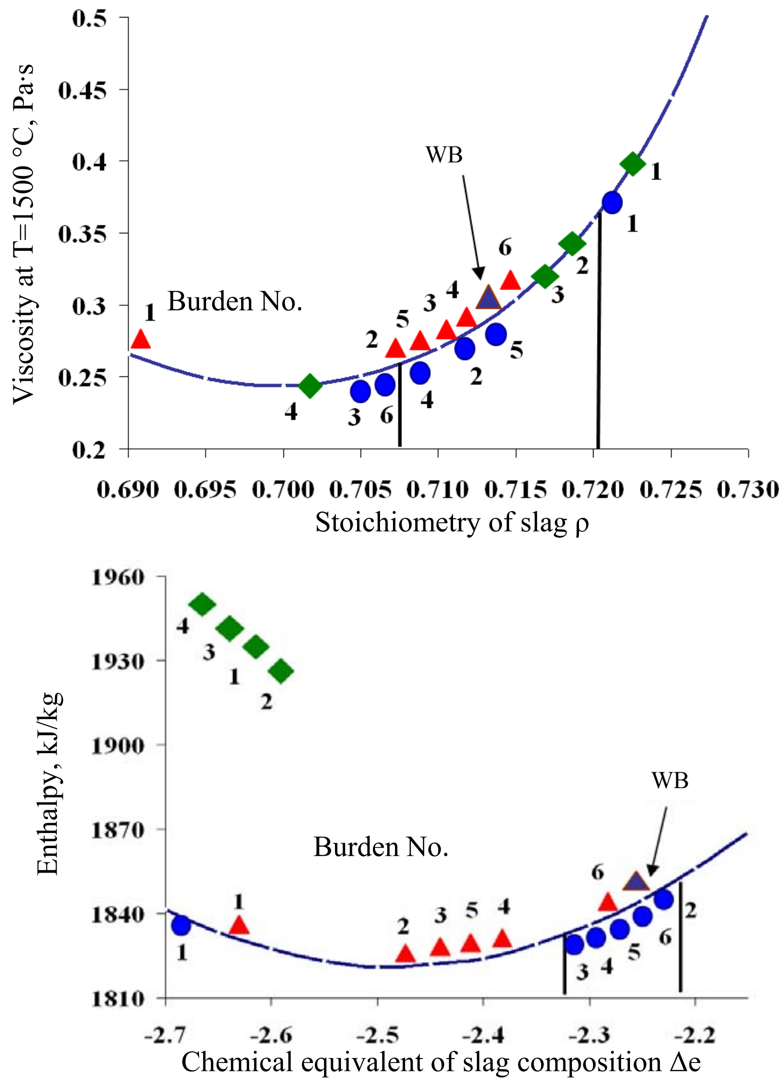

Figure 2. Time history of primary final slag properties of blowing-in burden in BF-8 (●); BF-9 (▲) JSC "ArselorMittal Kryvyy Rih" and BF-5 (♦) JSC "Severstal"

It is necessary to maintain this process for the first two days of blowing the furnace providing in this way the formation of high-strength slag lining.

As blowing charge goes to bottom of furnace shaft and bosh, fluxed part of blowing burden comes with almost formed final slag. Generally, this block consists of converter slag and crushed stone produced from blast-furnace slag. If consider that amount of slag per one ton of iron should be 0.8-1.2 t according to technology of blowing furnace, it is natural that physical properties of early slag will be defined by a system converter slag - blast-furnace crushed stone - coke ash. Viscosity of early slag is within 0.5-1.7 Pa·s at 1350 °C.

The following block of blowing burden is presented by iron-bearing materials and coke with cumulative ore loading. Thus, formation of early slag from these particular burdens will be close to usual at stationary regimes. As a result, as follows from **Figure 1** viscosity values from the last burdens will be almost equal. Behavior of slag viscosity values is almost ideal for all mix materials in blowing burden BF-8, 9. It was observed well in actual practice of furnace operation. Slag accumulated heat and was quite fluid when hot metal tapping. It proves to be true also by thaw point of early slag (**Figure 1**) as well as a significant amount of dirt in the first tapping due to good ability of final slag to flow.

As burden close by its fractional composition to work burden comes to zone of primary slag formation, heat of slag formation grows with increase of temperature as confirmed by computation-analytical experiment (**Figure 2**).

And though final slag for BF-5 JSC "Severstal" has higher heat content due to increased concentration of MgO, slag enthalpy growth trend for blowing burdens is similar to slag produced by Ukrainian plants.

To remove dirt, the blast-furnace hearth is washed in some days prior to furnace shutdown with addition of special flushing materials with certain properties into loading charge. Since flushing material melts are rather corrosive in relation to blast furnace lining, washing compositions and their charging regime are usually chosen proceeding from gathered experience and features of smelting as washing realization conditions are not specified in the technological instruction. To maintain stable running of blast furnace within the last 1-2 days prior to shutdown, thermal condition of blast-furnace hearth is raised due to ore load drop so that silicon content in pig-iron is 1.0-1.2 % and basic capacity of slag is (CaO/SiO_2) 1.10-1.15 units.

Usually, iron ore is used as a flushing material. Iron ore provides flowability of melt below viscous-plastic area and brings 35-40 % of ferrous oxide in the blast-furnace hearth which causes its high reactivity in relation to coke fines. Also manganese ore is added to improve drain ability of blast-furnace hearth.

Analysis of BF-9 final slag characteristics is shown in **Figures 3-4**.

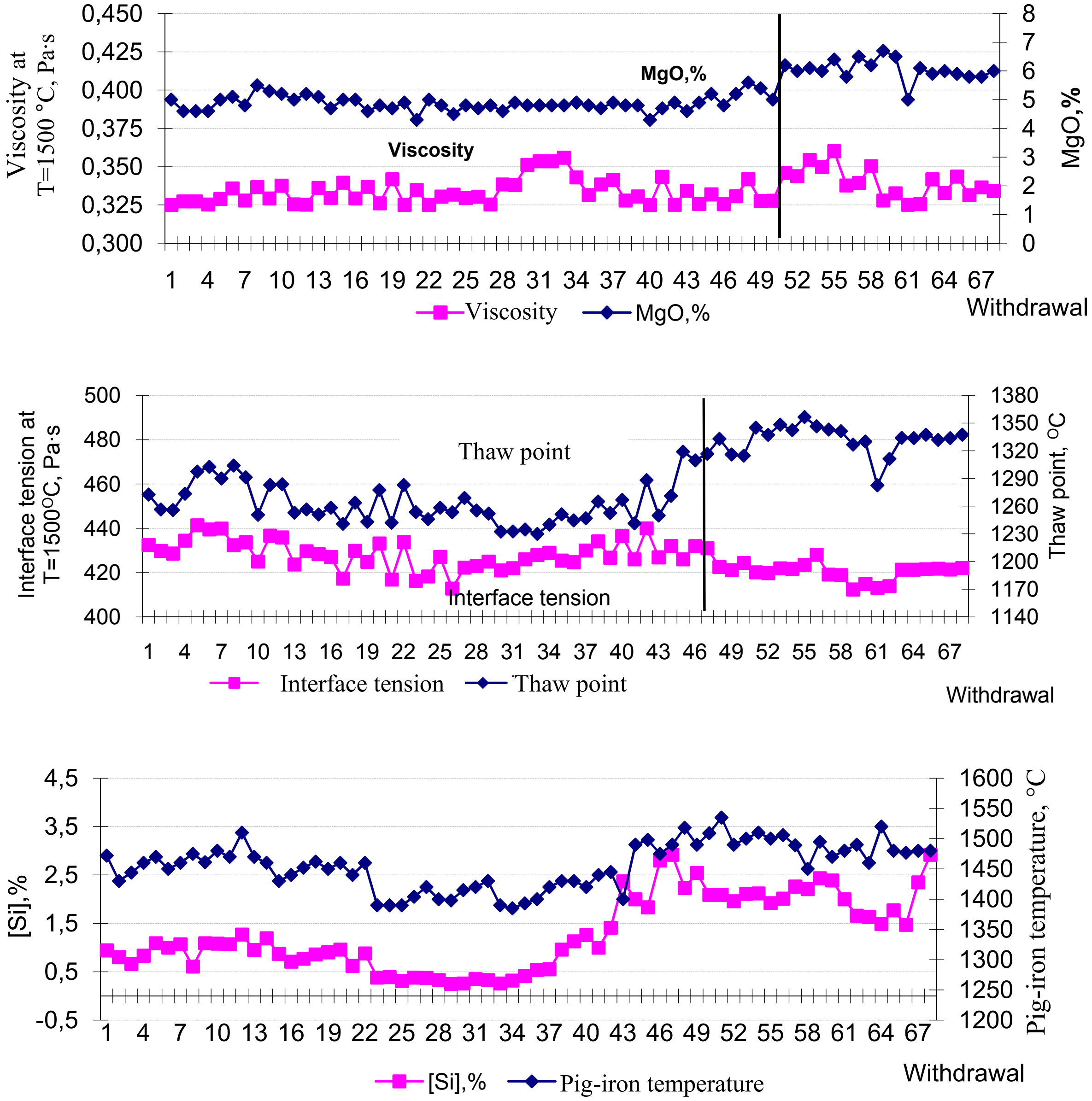

Figure 3. Change of iron and slag parameters during washing of blast-furnace hearth prior to blowing-out of BF-9 JSC "ArcelorMittal Kryvyy Rih"

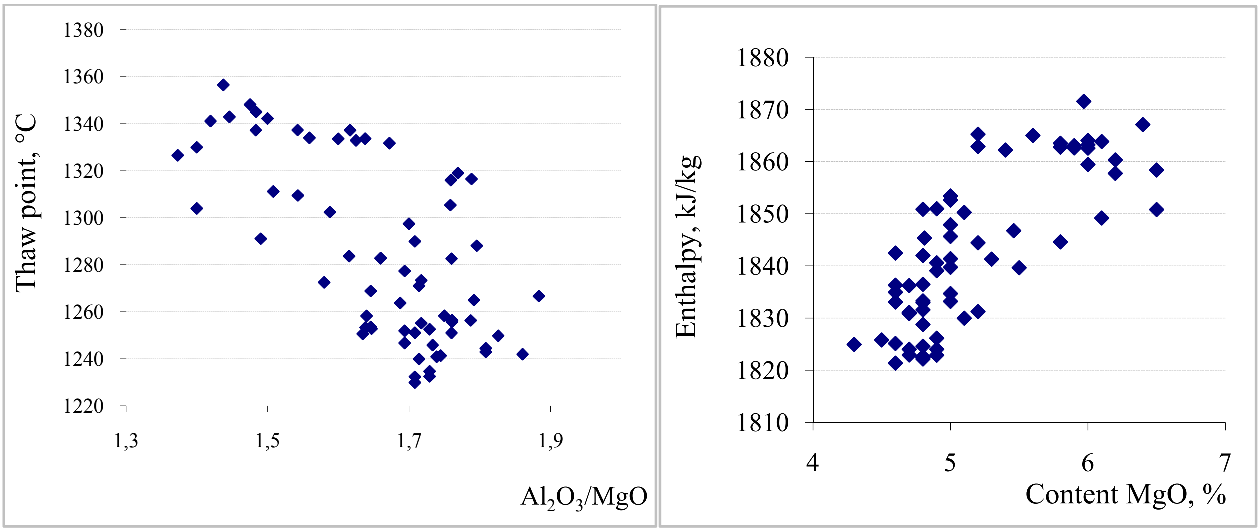

Figure 4. Dependence of properties on MgO content in the final slag at blowing-out BF-9 JSC "ArcelorMittal Kryvyy Rih"

Slag regime was unstable during preparation to blowing. As a result of unstable thermal condition of furnace bottom and silicon content in pig-iron (from 0.25 to 2.20 %) related to delivery of poor quality coke, basic capacity of slag by CaO/SiO_2 changed from 1.09-1.13 to 1.29-1.32 at adoption of cast iron smelting.

At Al_2O_3/MgO = 1.70-1.85 in final slag, properties of slag varied in a wide range which made drainage of smelting products difficult at raised viscosity and interface tension, reduced melting temperature even at high basic capacity. Increased content of MgO in the final slag (approximately by 1 %) at increased basic capacity (1.29-1.32) and low relation AI_2O_3/MgO (1.49-1.63) has improved viscosity of slag by the time of furnace blowout. Enthalpy increased at simultaneously increased temperature. Improvement of final slag properties caused improvement of drainage ability of blast-furnace hearth and promoted more uniform distribution of smelting products.

Conclusions

So, the limiting values of physic-chemical properties of primary and final slag providing stable running of blast-furnace, steady thermal and drainage condition of blast-furnace hearth in the working mode, during blow-in and blow-out of blast furnaces at Ukrainian plants are determined as a result of calculation-analytical evaluation of slag regime by means of system "Shlak":

- *during blowing-in* viscosity of early slag at 1350 °C should be within the limits 0.4-2.0 Pa·s with obtaining work burden with viscosity 0.3 Pa·s at T = 1500 °C; crystallization temperature of final slag not more than 1300 °C; interface tension of final slag 400-430 mN/m; enthalpy 1820-1850 kJ/kg;

- *in the working mode* viscosity is optimum at 1450-1550 °C not less than 0.25-0.26 Pa·s; end crystallization temperature not above 1300 °C; interface tension 420-440 mN/m; enthalpy 1830-1860 kJ/kg;

- *during blowing-out* it is necessary to provide: good flowability of slag with viscosity at 1450-1550 °C not more than 0.2-0.3 Pa·s; end crystallization temperature 1300-1350 °C; reduction of interface tension to 410-420 mN/m; raise of heat content (enthalpy) to level of 1840-1870 kJ/kg.

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Аналитическая оценка свойств доменных шлаков, обеспечивающих устойчивую работу печи в нестационарных условиях

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С использованием системы контроля и управления шлаковым режимом доменной плавки выполнены расчетно-аналитические исследования состава и высокотемпературных свойств шихтовых материалов и соответствующих им свойств первичных и конечных шлаков из задувочных шихт и в период остановки печи на капитальный ремонт для условий работы доменных печей ОАО «АрселорМиттал Кривой Рог» и ОАО «Северсталь». Установлены предельные значения физико-химических свойств первичных и конечных шлаков в рабочем режиме, в периоды задувки и выдувки доменных печей в сырьевых условиях заводов Украины.